Chapter 2

FROM BUNSEN BURNER TO HEAT RELEASE RATE CALORIMETER

by

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EARLY HISTORY

Fire performance of buildings, transportation vehicles, and other occupied spaces has traditionally been viewed as having two main aspects: flammability and fire endurance. Flammability (or, 'reaction to fire') is a very imprecise term, however, it normally includes ignitability, flame spread, and heat release rate. Fire endurance refers to the performance of the structure itself, that is, does it collapse during the fire, and do any of its internal compartment separations fail.

Standard methods for fire endurance testing date from the 1903 International Fire Prevention Congress [1]. Actual development of these concepts goes back another two decades, to the 1880s and 1890s [2]. Concern with developing standard testing methods for flammability, however, does not have such a long historical basis. At the turn of the century, some concern about materials' flammability was raised after disastrous theatre fires. Investigators studying such fires invariably recommended that less flammable stage scenery and decorating fabrics should be adopted. The most extensive early investigation was by the famed American engineer John R. Freeman [3]. He reported developing in 1905 a 'stovepipe' test, whereby strips of test cloth were hung inside a 2-foot high chimney, and lighted by excelsior kindling at the bottom. This was not a readily portable test so he also commissioned the development of an alcohol-lamp field test. This was known as the Whipple-Fay test, after the names of the two persons hired by Freeman to develop the test. Neither of these became a standard test. Tests for the flammability of textiles were not standardised in England until the alcohol-cup test of the British Standards Institution in 1936 [4], and in the United States until the first version of the current NFPA 701 Bunsen-burner test was proposed by the National Fire Protection Association in 1938 [5].

Concern about the flammability of textile products, both in the form of curtains or drapes in buildings, and as clothing apparel, may be very essential. These

products, however, are typically encountered in fires where heat release rate concerns are not dominant. Flame spread tends to be, by far, the dominant factor with textiles, supplemented by aspects of ignitability, extinguishability, and — in the case of apparel — injury potential due to direct heat flux. Fabrics, as normally used, are much thinner and lighter weight than most other combustibles prone to be involved in fire. Thus, the total heat available to be released is never large, and even the peak value of heat release may not be very great, compared to other articles. The ability of certain fabrics to spread flame very rapidly can, however, be striking.

With most other articles of greater weight and thickness, the heat release rate, flame spread, and ignitability may all need to be considered. In many applications, it is found that these three variables may be highly correlated. In other applications, it is found that ignitability, say, may be little affected by changes in specimen composition. With the exception of textile products there are few applications, where the heat release rate characteristics are of only minor importance.

Among products which are not textiles, the earliest concerns involve the burning rates of wood, and the efficacy of fire retardant treatments for wood. In 1902, the pioneering Columbia University professor Ira H. Woolson started working with
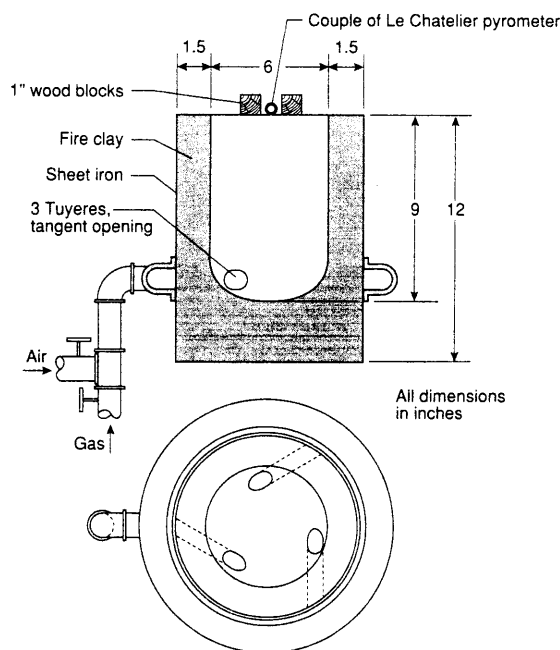

Figure 1. The Timber test.

the U.S. Navy to develop a standard test for the burning behavior of fire retardant wood [6]. This test was called the 'timber test,' and became somewhat well-known, although only for the limited application of testing fire retarded woods (Fig. 1). This was, in fact, the earliest standard flammability test on record. Later, additional specialized test methods were devised for that purpose [7]in the 1920s. The first Bunsen burner tests for plastics were being developed as early as 1940 [8].

A more wide-ranging concern with flammability was seen with the introduction of the Steiner Tunnel Test in 1943 [9]. This particular method is still in wide use today. It is primarily a flame spread test, but does also have a 'fuel contributed' measurement component, which can be taken to be a crude form of heat release rate. In recent years, this 'fuel contributed' measurement has been de-emphasized, and the current ASTM procedure no longer requires that a specific classification be derived from it [10].

During the 1950s and the 1960s, there was an increased reliance on testing the flammability of materials by means of Bunsen burner type tests. By 1973, however, the U.S. Federal Trade Commission thought that misrepresentation of the burning properties of plastics in Bunsen burner tests had become of such concern as to require an action against some two dozen manufacturers [11]. A consent agreement was eventually reached, whereby a Bunsen burner test, ASTM D 1692, which was the most notorious of these, was dropped, and a *caveat* was inserted into other ASTM (American Society for Testing and Materials) tests, in an attempt to avoid their misuse.

SMALL-SCALE HEAT RELEASE RATE TESTS

The FM Construction Materials Calorimeter

The earliest test method developed specifically for measuring heat release rate was the FM Construction Materials Calorimeter, developed by Thompson and Cousins at the Factory Mutual Research Laboratories in 1959 [12]. This was a medium-sized apparatus, with a specimen size of 1.22 m by 1.22 m (Fig. 2). The specimen was tested in the horizontal, face-down orientation. The principle of apparatus might best be described as a 'substitution test.' A specimen was inserted into the apparatus and subjected to a prescribed exposure from an oil burner fire. The exhaust stack temperature was recorded, as a function of time. A second test run was then made, with a non-combustible blank substituted for the specimen. Propane gas was metered into the evaluating burners (Fig. 2), with the flow being adjusted so that the stack temperature record would duplicate the earlier result. The combustion energy represented by the metered propane was then taken to correspond to the heat release rate of the specimen.
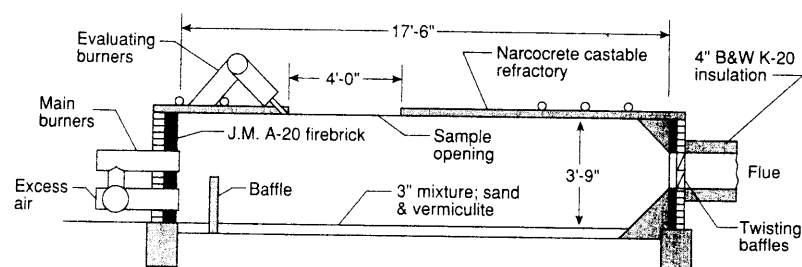
Figure 2. The FM Construction Materials Calorimeter.

This method, *mirabile dictu*, is still in use by FM today as part of an approval standard for steel deck roofs [13]. Outside of FM laboratories, this method did not come into more widespread use. Its main difficulty was that it was a cumbersome test — not only were two runs required for each test, but also the apparatus had to be cooled off to ambient before the second run could be made.

The FPL Calorimeter

Some years later, a calorimeter was built by Brenden at the U.S. Forest Product Laboratories (FPL) which was similar in operating principles to the first FM unit, although of different physical design [14]. The FPL calorimeter used vertically oriented specimens, 0.46 m by 0.46 m in size, and was fired with a natural gas burner (Fig. 3). Although in this design the need for having uniform
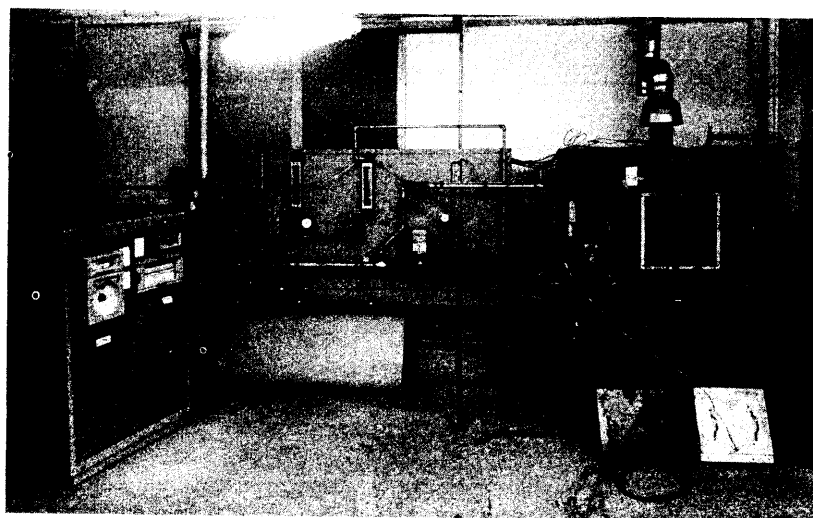

Figure 3. The FPL Calorimeter.

irradiance over the specimen face was more clearly evident than in the earlier FI work, uniformity of irradiance was still poor. A maximum of about 35 kW/m could be achieved, but heat flux variations over the face of the specimen were i the 40% vicinity. This calorimeter did not come into wider use, outside of th U.S. Forest Product Laboratory.

The NBS-I Calorimeter

By 1972 an improved design principle was available. It was discovered by Parkι and Long [15]that an instrument could be made which was related to th substitution-test type design, but which would not require two runs per specimeι and which would be true to the actual time-resolved nature of the specimen' combustion. In present-day terminology this would be called an 'isotherma design (Fig. 4). In this design, a control section is established in the stack, wheι thermocouples are used to monitor the temperature of the exhaust gases. A auxiliary burner, supplied with propane, is located some ways above th specimen. This burner is lighted prior to test, with the propane flow rate set ι a maximum value. The valve controlling the propane flow is put into a serv loop, with an array of thermocouples, located in the exhaust stack, being used fc setpoint sensing. When a specimen ignites and releases heat, a rise of th thermocouple temperature would ensue. Because of the servo loop, however, thι
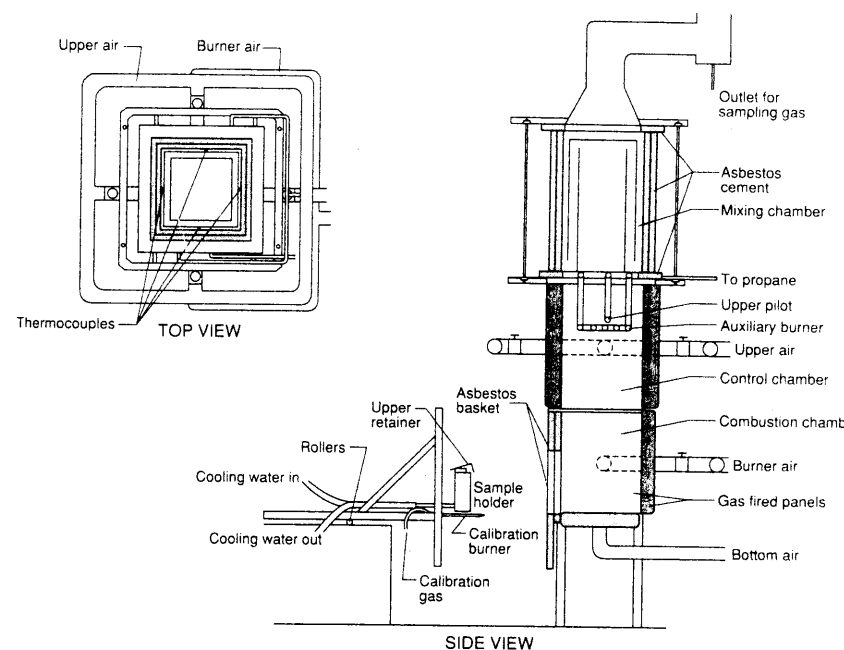

Figure 4. The NBS-I Calorimeter.

increased heating is sensed, and the control valve to the auxiliary burner turns down the gas flow to the auxiliary burner, maintaining the thermocouples at the setpoint temperature. The heat release rate is determined by including a mass flow measuring device in the propane supply line. The specimen's heat release rate is, then, equal to the decrease in the propane flow, expressed in heat units.

The apparatus was originally designed to test only 114 × 152 mm specimens, up to 25 mm thick, exposed in a vertical orientation. A maximum heat flux of 100 kW/m^2 could be applied on the specimen, although such high heating fluxes were not recommended to be applied for extensive durations. In the previous instruments, no special efforts were made to establish the conditions at the specimen's unexposed rear face. By contrast, the original NBS-I calorimeter was provided with a water-cooled backing plate to the specimen, so that the heat losses from the back might be measured by determining the temperature rise of the cooling water. In later years, a provision was made for also testing horizontally (face-up) oriented specimens.

This instrument significantly simplified testing, since it no longer required extensive calibrating runs for each test. The system was still not without its limitations, however. These included the high complexity of the apparatus, the sensitivity to exhaust pressure fluctuations, and the need for a long equilibration time prior to test. The latter arose from the fact that the exhaust gases also flowed past the heating panels which were providing irradiance to the specimen. If there was a temperature change in these, it would also affect the temperature at the thermocouples. An anomaly was also observed when the specimen door was opened to insert a specimen — this would admit cold room air into the apparatus and, therefore, register as negative heat release. For a rapidly igniting specimen, a return to equilibrium might not happen before the specimen already ignited and started burning. An apparatus of this type was available only at NBS. The NBS-I calorimeter was eventually replaced by the NBS-II instrument and was removed from service.

The SRI calorimeter

While the NBS-I calorimeter was not put into wide use, its design inspired at least one other instrument. Martin at Stanford Research Institute (SRI) [16]constructed in 1973 a nearly identical, but scaled-up unit. The SRI calorimeter accommodated vertical specimens 457 × 610 mm in size, with a usable flux range of 15 to 70 kW/m^2. For specimens of the above size, the maximum usable heat release rate range was restricted to a rather small value of about 120 kW/m^2, although much higher values could be recorded if specimen area was cut down. This apparatus was not much used. With the disbanding of the fire research group at SRI, the apparatus was transferred to Lawrence Livermore Laboratories (Livermore, CA), where it is still used occasionally.

The OSU calorimeter

The Ohio State University (OSU) calorimeter was first described by E. E. Smith in 1972 [17]. It embodies rather different principles than the preceding units. Due to its simple, low-cost construction, more units of this design (several dozen) were placed into service than all previous types combined; thus, its features will be discussed in somewhat greater detail. All of the prior units encompassed some idea of heat substitution, whether sequentially, in the same spot, or simultaneously, but offset in location. The OSU unit used a much simpler concept, that of the well-insulated box. According to basic principles, one could build an 'adiabatic' heat release rate calorimeter. In such a device, the walls would — by definition — have no heat losses associated with them. The heat contributed by the specimen would be manifested directly as the difference between the sensible enthalpy[1] of the incoming, and the exiting air stream. It is, indeed, possible to build adiabatic walls. These are normally active systems, whereby the temperature gradient across a thickness profile is monitored; a feedback loop is then used to supply heat to an interstitial heater to maintain the effective gradient — and, therefore the heat transfer — at zero. Such an arrangement is often incorporated into instruments for measuring thermal conductivity [18]; however, to make up a heat release rate calorimeter in this fashion would be costly and has never been attempted.

Instead, the OSU apparatus involves nothing more than a moderately insulated box (Fig. 5). The original design used three thermocouples in the exhaust stream and three more in the air intake stream. Each set of three was connected series-boosting, with the two sets being hooked one series-bucking to the other. Shortly afterwards, the measurement scheme was simplified by eliminating the set of three intake thermocouples. With a non-adiabatic box, however, the measurement of the enthalpy of the outflow stream, only gives relative numbers, and is, in fact, not uniquely related to the heat release rate. Using a known gas flow rate through a burner, a calibration factor can be derived relating the thermocouple reading to the heat release rate. This calibration factor, unfortunately, is not a constant, and is directly affected by the inlet air temperature and flow rate, and also by the amount of heat being put out by the radiant panel.

Since the instrument does not have adiabatic walls, the heat losses to the walls are the highest at the start of a test, decreasing later, as the walls heat up from the burning specimen. The heat that goes into the walls represents an error term,

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[1] The term enthalpy in thermodynamics is the generalized concept of heat content. For systems where the operation is carried out in a constant-volume mode, energy changes would be relevant. Most combustion processes of interest, however, take place under constant-pressure, not constant-volume conditions. For such systems, the change in enthalpy, ΔH_{ab}, going from state a to state b is: $\Delta H_{ab} = (E_b + P_b V_b) - (E_A + P_A V_A)$, where E, P, and V, and the energy, pressure, and volume, respectively. Sensible enthalpy refers to that enthalpy component which does not include 'latent' terms, i.e., heats of isothermal phase change.
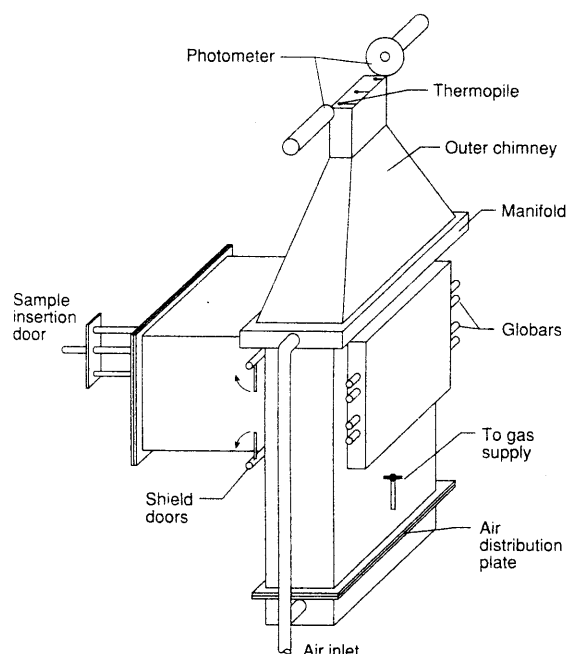
Figure 5. The OSU Calorimeter (ASTM E 906).

one which is greatest during the early portions of a test. Thus, if one were to try to calibrate the instrument with a burner to which a steady gas inflow was furnished, the chart recorder trace denoting the heat release rate would not give a square-wave function, but, rather, a curve gradually rising towards a plateau. The solution to this was to provide a 'compensation tab.' This comprised a fourth thermocouple, wired series-bucking against the three main thermocouples, which were hooked up series-boosting. The bucking thermocouple was then physically mounted not in the outflow airstream, but connected to a small metal plate fixed to the inside instrument wall. The bucking signal from this thermocouple was the smallest at the start of the test, when the wall was still cool, and progressively increased later when the wall temperature rose. Thus, it diminished later readings more than earlier ones, and served to help flatten out the calibration curve. With this device in place, however, all notion of quantitative accounting for the heat flow was left behind, since now the thermocouple signal did not even represent the enthalpy of the exhaust stream directly. This compensation tab technique was adopted by ASTM, when it published the OSU apparatus as its standard E 906 [19], but was not adopted by all users. Chapter 17, for instance, details the stance of the FAA in this matter.

The OSU apparatus initially used a gas-fired heating panel. This was later replaced by an electric radiant panel. In the ASTM E 906, the heater is currently

specified as four electric heating bars made of silicon carbide. In the experience of NIST, these heaters were a source of difficulty for two reasons — the continual aging and decreased output from the elements, and their brittle nature and propensity to fail catastrophically.

Initially, the specimen size was fixed at 254 × 254 mm, and only a vertical specimen orientation was provided for. Later, due to problems of inability to uniformly heat the area, and to dissipate the heat generated by faster-burning specimens, the vertical specimen size was reduced to 150 × 150 mm. A provision was also added to test specimens in the horizontal mode, the specimen in that case being 110 mm × 150 mm. The horizontal specimen orientation is established by installing an aluminum foil reflector, to act as a mirror directing radiation downwards. In practice, this arrangement was seen to lead to a dropoff of around 50% of the centerline heat flux at the edge of the specimen. Of even greater concern was that the aluminum reflector melts as specimen flames impinge upon it!

A notional upper limit heat flux of 100 kW/m^2 in the vertical orientation has been specified [19], although it appears that few users have been able to consistently approach such heating levels. A maximum heat release rate of 8 kW is specified, governed mainly by the need not to have flames project beyond the stack exhaust. The maximum per-unit-area heat release rate then depends upon the specimen size.

Although various pilot arrangements have been used in this apparatus, the most common one has been a gas pilot which is operated as an 'impinging' pilot. In such a configuration, a relatively large flame is used, and the pilot is held close enough to the specimen that it provides significant additional local heating.

The OSU apparatus also is typically outfitted with a smoke measuring photometer. Because of the crude nature of that device, however, these measurements have not been commonly reported.

Because at one time there were quite a few of these apparatuses built, a number of researchers over the years have studied some of the theoretical or operational difficulties with the OSU Apparatus. One of the first studies was by Krause and Gann [20]. They found that the apparatus, when correctly calibrated with methane, substantially under-reported the heat release of soot-producing specimen. A rough correlation of increasing error with increasing soot yield was observed. Later, similar experiments were repeated by Babrauskas [21], taking into account some of Smith's objections to the first study [22]. The study by Babrauskas was conducted on horizontal-orientation specimens. The findings of Krause and Gann were substantively confirmed. In addition, new problems emerged. HRR data showed errors due to uncontrolled irradiance towards the specimen. Unlike in instruments of more current design, once a

specimen ignites and produces flames, the power to the heater is not automatically turned down; thus, the heater face temperature rises to values greater than it was during the calibration procedure[2]. Similarly, the specimen receives additional unintended heating from other ironwork in the vicinity, which has also been raised in temperature. In the horizontal orientation, this problem is made worse by the fact that specimen flames impinge provide a much greater heating by directly on the nearby ironwork. In the horizontal orientation there are also an additional error when the aluminum reflector foil melts and the fraction of heater radiation directed towards the specimen changes.

A thermopile-sensing method, such as the OSU, depends on the relationship of HRR to the arbitrary chart voltage out being identical during a test burn as was during the calibration procedure. Gross [23]and Tran [24]conducted investigations on this question in the OSU Apparatus. Gross found that when a calibration factor of 0.148 to 0.155 kW/chart division was recorded with the apparatus heater off, the factor rose to 0.19 - 0.23 kW/chart division when the heater was turned on and set to the 25 kW/m^2 irradiance level. Tran verified Gross's finding and also documented a related problem—the calibration factor also varies with the HRR, not just with the heater irradiance. As an example, when the HRR rose from 1.58 kW to 4.74 kW, the calibration factor increased by 10%. Based on these and other studies, Tran [24] re-affirmed the earlier fihdings of Krause and Gann, Babrauskas, and Blomqvist [25]that measurement errors are much reduced in the OSU apparatus if oxygen consumption, not thermopile sensing, is used as the measurement method. This is also the opinion of other active workers (e.g., [26]) still doing research with the OSU apparatus.

Limitations of the OSU apparatus, however, were not confined solely to errors in determining the HRR. These included:

1)   the lack of provisions to measure specimen mass loss rate;
2)   serious problems with pilot arrangements (they cause unanticipated heating to the specimen, or are extinguished by fire-retardant containing specimens);
3)   long times needed to re-equilibrate the apparatus for the next test;
4)   the inappropriateness of the design of the accompanying smoke meter [27];
5)   the lack of temperature control on the heater, along with unaccounted-for heating of specimens by hot ironwork;
6)   the difficulties in making the box gas-tight, and the accompanying danger of fire spreading to the outside of the equipment;

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2   We are not considering here the added contribution to heating the specimen from the specimen's own flame; this is proper and is not an error term. What is an error is if the heater radiation, which is supposed to represent the 'far field,' prescribed fire conditions, changes to something other than the value set during calibration.

7)   the lack of a viable mode of horizontal orientation testing (due to higher errors associated with horizontal testing, this mode testing has largely been abandoned);
8)   the difficulties many laboratories have had in reaching and maintaining higher irradiances (50 to 100 kW/m^2);
9)   the problems associated with aging, drift, and abrupt failures of the silicon carbide heating elements;
10)   the lack of robustness of the equipment (to minimize warm-up problems, both the apparatus itself and the specimen holders are made of thin gauge metal, which causes problems with warping);
11)   the very serious difficulties in conducting routine calibrations of both the irradiance and the HRR.

Over the years a number of workers have suggested various improvements that could be made to the OSU apparatus to eliminate or reduce some of the above problems. Unfortunately, none of these suggestions have, so far, been reflected in the test standard as published by ASTM

The FMRC small-scale flammability apparatus

The FMRC (Factory Mutual Research Corporation) small-scale flammability apparatus was first described by Tewarson in 1975 [28]. The original apparatus has never been proposed for standard products testing use; however, it embodies some novel design concepts, and has been used by several additional laboratories, in addition to FMRC. Figure 6 shows a general view of the apparatus. Test specimens are 100 mm in diameter, and up to 50 mm thick. Specimens are tested only in the horizontal, face-up position, in part, because FMRC desired to test liquids on the same basis as solids. Specimen heating differs substantially from previous designs, in that a bank of quartz lamps is used as the source. The apparatus was the first to incorporate a load cell for obtaining a continuous specimen mass loss record, and also the first one to allow the introduction of non-ambient combustion air supplies. The earliest design already provided for a variable O_2/N_2 mixture, while later revisions added an inlet air heating system, although the latter has not been used extensively.

Measurements of the enthalpy of the exhaust stream are made; however, these are appropriately identified as only the convective component[3] of the total heat release rate. This total heat release rate was originally obtained by a computation

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3   Dr. Tewarson and his co-workers report not just the heat release rate, which they somewhat redundantly refer to as the *chemical heat release rate*, but also separately the fraction that is measured as convective and as radiative. Such classification has not found much acceptance outside of the FM System. The reason is that heat output does not stay 'tagged' as to whether is was convective or radiative. If a heat balance is done on the same products of combustion further downstream, it will be found that the convective/radiative fraction has changed.
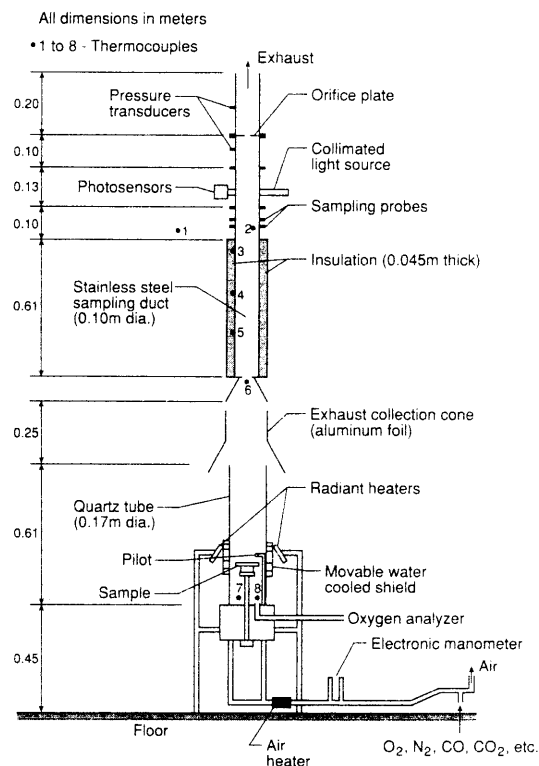
All dimensions in meters

• 1 to 8 - Thermocouples

Figure 6. The FMRC small-scale flammability apparatus.

involving the specimen mass loss rate, the oxygen-bomb value for the heat of complete combustion, and the fraction of specimen mass which becomes carbon dioxide (CO_2) and carbon monoxide (CO). In some later work, the concept of oxygen consumption (see Chapter 3) was adopted [29]; however, a variant procedure based on determining the heat release rate from CO_2 and CO production, but without oxygen bomb measurements, is also used [30], [31].

The quartz lamp heaters can provide a specimen heating flux of up to 65 kW/m². The maximum measurable specimen heat release rate is reported to be 10 kW. The largest application of the apparatus has been to liquid samples and polymeric samples presented as resin beads. While geometrically more difficult specimens, such as electrical cables, have been successfully tested, nonetheless the use of a round specimen shape has lent itself most readily to specimens not requiring extensive edge preparation.

The apparatus has also been provided with a smoke photometer and gas analysis

instruments. The products of combustion from the apparatus have even been used for exposing animals to a fire toxicity test [32].

The modified FMRC flammability apparatus

In a move to distinguish their capabilities from other HRR work going on, FMRC recently put the apparatus to use for the testing of scaled-down commodities. These have included cardboard boxes, pallet loads, and, especially, electric cables [33]. The apparatus was hitherto a straightforward bench-scale HRR calorimeter. In such a calorimeter, the exposed surface area is precisely defined and pains are taken to make sure burning is as uniform as possible over this entire exposed face. The data, in consequence, can then be reported in units of kW/m², where the m² refers to the area of the exposed specimen face. Such standard testing normally requires specimens which have a flat face, or one nearly so. This exposed specimen area is then expected to be heated with as uniform a radiant field as is possible. In the new FMRC configuration, miniature commodities are constructed. For boxes, it is a miniature box. For cables, it is a vertical length of cable, the bottom end of which is inserted into the radiant field of the apparatus. The bottom portion of the cable then is ignited and is heated by the irradiance from the heater. The remaining length is not heated, but does get burned when flames spread upward on it. The specimen area burning at any given time is not well-defined. Also, the external irradiance on the specimen is no longer a constant but varies from the prescribed value at the lower end to near-zero at the upper. Thus, data from it can no longer be evaluated in meaningful kW/m² units, and we would not consider it an example of a bench-scale HRR calorimeter. Instead, the apparatus becomes a bench-scale scale model of a fire of some given commodity. The topic of geometrically scaled fire tests is outside of the scope of the present book.

The modified FMRC Flammability Apparatus is normally operated under conditions where the O_2 content of the combustion air is set to 40%. FMRC did this since they wanted to impose a heat flux on the specimen beyond the 65 kW/m² available from the heater lamps. This higher value is said to be a better approximation to the higher flame fluxes which occur in full-scale fires. This concept is novel to FMRC and has not found much acceptance elsewhere, for the following reason. The radiant flame flux can be viewed as consisting of two primary factors, emissivity ε and flame temperature T_f. When the scale of fire changes, the emissivity changes; by contrast, T_f changes little with scale. Adding O_2 to the combustion air, however, raises T_f and not ε. The effect is not interchangeable, since the action of fire retardants can be quite sensitive to T_f.

FMRC Intermediate-Scale Flammability Apparatus

FMRC have also extended their approach to small-scale heat release rate measurements by constructing a scaled-up version of the original small-scale

Flammability Apparatus. This equipment uses the same instrumentation and analysis as the small-scale Apparatus. The physical construction is also highly similar, changed only where necessary to be accommodated in a standard laboratory height space. The device has been described by Newman and Khan [34]; the main change is a specimen size of 305 mm diameter, by 75 mm thick, and a corresponding scale-up of the other apparatus dimensions. The instrument is considered to be capable of measuring specimens showing a heat release rate of up to 500 kW. Very few results have so far been reported [34], [35].

NBS-II calorimeter

The origins of this apparatus were similar to those of the SRI calorimeter — a desire to scale up the NBS-I unit, and at the same time to introduce a number of other instrument and operational improvements. The calorimeter has also been called the 'Tordella Calorimeter,' since it was designed by Dr. John P. Tordella, of E.I. Du Pont de Nemours & Co., while he was a research associate at the National Bureau of Standards during 1976-78 [36].

The apparatus was intended to be more rugged, easy to use, and to be less susceptible to certain sources of error identified on the NBS-I unit. The specimen dimensions were chosen to be 300 × 300 mm for the vertical orientation, and 150 × 300 mm for horizontally, face-up oriented specimens. Figure 7 shows the general view of the apparatus. The NBS-II was designed to provide from 25 to
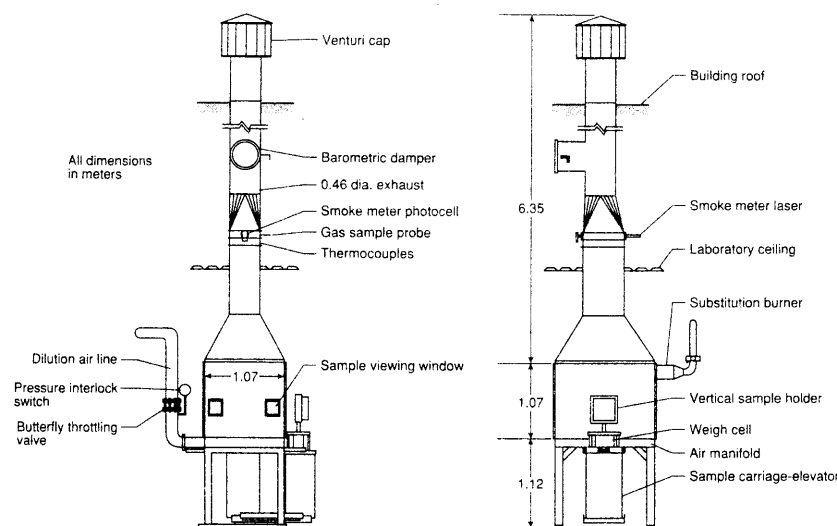
Figure 7. The NBS-II Calorimeter.

80 kW/m^2 irradiance for specimens in either orientation. A maximum heat release rate measuring capability of 1000 kW/m^2 was provided for vertically oriented samples, with twice that for horizontal ones (due to there being half the specimen area).

The unit was successfully placed into operation in 1978. By 1982 progress in the field made desirable other approaches (see the chapter on the oxygen consumption calorimetry), and the unit was taken out of service.

Despite the short period of its use, a number of engineering advances were made with this unit. One of the most significant was the realization in its design that there should be a minimum of surfaces present inside the test chamber where there are surfaces which have a significant view angle to the specimen, are free to rise and fall in temperature, and are not thermostatically controlled. For a specimen in the horizontal orientation, such a source of error in the specimen heating was minimized with the NBS-II design by providing for an array of radiant heating panels to cover all four sides of the chamber. The specimen was introduced from the bottom, by a pneumatic elevator. Thus, the specimen was not seeing any nearby surfaces made of firebrick (on the NBS-I, by contrast, a horizontal specimen would view an uncontrolled surface on one of the four sides). In the vertical orientation, the original design envisioned shutting off half the radiant panels, so that a specimen would be heated only from its front face. In practice, it proved to be difficult to achieve a linear calibration under these circumstances. Thus, the design was modified so that in the vertical orientation there were two specimens, back-to-back, and all the radiant heating panels remained in use.

An additional feature of elegant design was the elimination of all heavy firebrick surfaces. The outside of the instrument comprised a highly rigid structural frame, filled out with lightweight stainless steel wall panels. In between the wall panels and the back surfaces of the heater panels, there was introduced a flow of secondary air. This acted to rapidly equilibrate the apparatus to a given temperature. A substantially improved thermocouple measuring section with its attendant mixing chamber were also provided.

A major feature of the new apparatus was that provisions for a load cell were made from the very start, so that there would be a continuous record of the specimen mass loss. This was incorporated into the pneumatic elevator assembly, and used water cooling both on its sides and through the top portion of the weighing platform itself.

Another innovation was a thorough exploration of new ways to provide specimen ignition. Two modes of gas pilot ignition were incorporated: in one mode a 'curtain' flame could be applied over the face of a vertical specimen; in another mode, the specimen was ignited at the bottom by a small gas pilot. These types

of ignitions were restricted to specialized uses. For normal operation, electric spark ignition was developed. This proved to be very reliable and formed the basis for further developments of pilot arrangements in other devices at NBS.

The apparatus, as constructed, worked generally to specification. Problem areas included the inability to test single-sided vertical specimens and the sensitivity of the response to barometric pressure variations propagating down the exhaust system. The large specimen height, and vertical samples orientation leads to some materials melting out or buckling out of the specimen holder well before completing their combustion. A more serious obstacle to adoption by other laboratories was the fact that the apparatus, as built, was a very cumbersome industrial-scale machine, requiring a high-pressure natural gas supply, a very large air compressor, and several other difficulties of construction and installation. Thus, its uses were restricted to exploratory research studies. Two such studies were published [37], [38]. More important, however, was its role as a test bed in developing new concepts. Oxygen consumption measurements were implemented in it as part of such studies. These eventually pointed to an instrument of an entirely different sort as being more suitable for routine testing purposes.

The TRADA/ISO Apparatus

By the 1970s, while there had been diverse research efforts in the area of bench-scale heat release rate measurements, yet there was no standard method being offered. Thus, an effort was started in Europe to design and construct a bench-scale rate of heat release apparatus which would be suitable for standard testing. The work was being encouraged by ISO (International Organization for Standardization) and initially was performed at the Timber Research and Development Organization (TRADA), located in High Wycombe, England. Their development work is described in a 1977 ISO document [39]. Some of the early work was also supported by the Fire Research Station, Borehamwood, England. In 1978, work on the apparatus was taken over by DANTEST in Copenhagen, Denmark [40],[41],[42].

The apparatus underwent many modifications in the process of its development, and never did reach a state of evolution sufficient for ISO to espouse its adoption. Figure 8 shows the status *ca.* 1977. The description below is a brief summary of an extensive development project, where even the basic features of the instrument were changing drastically during development. Basically, it was a closed box arrangement, used for testing specimens of 0.3 m by 0.3 m in area, and up to 0.05 m thick. Specimen orientation was selected by re-orienting the entire apparatus around a rotary mount. The heating source was initially a propane gas radiant burner. This burner arrangement could provide no more than 30 kW/m² irradiance safely. At DANTEST, it was later replaced by an array of
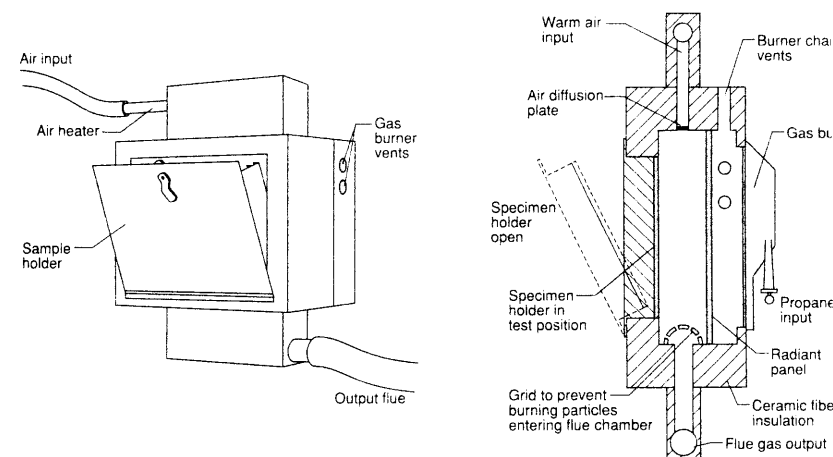

Figure 8. The original TRADA/ISO apparatus.

silicon carbide heating rods, covering an area of 0.38 by 0.38 m and providi a maximum heat flux of 60 to 70 kW/m². Air flow was provided by a centrifu, blower forced air supply, at a rate of 500 to 800 ℓ/min. An unusual feature the air flow system was its direction — down, over a vertical specimen. This w said to improve uniformity, even though a certain realism was lost. The sup air, instead of being pulled in directly from the laboratory, was first pass through a heater, where it was heated up to 100 °C. Since the apparatus was built gas-tight, it was necessary to maintain the test chamber pressure at atmospheric level, lest there be in- or out-flows through the cracks. Thus scheme for pressure balancing was devised whereby an eductor was located in exhaust duct, driven by a combination of high pressure water spray and co pressed air, was used. For piloting arrangements, either a series of 4 hot w coils or four hydrogen-air flame pilots were used. (Earlier work had establish that propane-air pilots were not sufficiently resistant to blow-out.)

The rate of heat release was measured in the original version with an exhaust fl thermocouple, much as used in the OSU test. Peak heat output capacity w stated as being 10.5 kW for older versions, and up to 12 kW for the last versic This is a rather low value in view of the specimen size; recommendations we made suggested halving the size of the specimen [41]. There were also seric problems of the actual shapes of the RHR curves not tracking those expected d to the slow response time of the insulated box system. In their 1979 repc DANTEST [41] thus concluded that '...the use of the closed-box system does r allow for the possibility of obtaining quick answers to heat response signals. T possibilities for obtaining radically improved temperature-time characteristics ; rather limited...' Thus, in the final version of the test apparatus [42] oxyg consumption was used as the measurement method. The specimen area was al

reduced, to 0.23 m by 0.23 m, inclusive of a 15 mm lip around the edge. Specimen maximum thickness was raised to 0.125 m. While no gas analysis was made in the original design, in the O_2-based version gas analysis was, of course, mandatory. The exhaust ducting arrangements for making the gas measurements were similar to those used in the Cone Calorimeter. In none of the versions was there any provision for measuring the mass loss rate. This proved to be significant drawback. Also, once the oxygen consumption principle was adopted, it was evident that an insulated box was no longer the optimal specimen exposure chamber. Thus, development work stopped. In 1983 ISO, instead, made the commitment in its Working Group that further development would be based on the Cone Calorimeter [43].

The Sensenig apparatus

Initial measurements of oxygen consumption for heat release rate purposes were made by William Parker during a 1974 study of the Steiner tunnel [44]. This work did not yet lead to the development of practical instrumentation. As a subsequent work item, however, during 1976 and 1977 D.L. Sensenig, from Armstrong Cork Co., as a guest researcher at NBS, set to developing a simple bench-scale rate of heat release test. His apparatus is shown in Fig. 9, and comprised a flat-panel electrical heater, a specimen load cell, and an exhaust system where O_2 measurements were taken [45]. This experimental apparatus was used for only a very few tests, before it was supplanted by later developments; thus, no extensive characterization of its limits was made. In the history of rate of heat release testing, however, it was important in that it demonstrated to a wide audience the viability of oxygen consumption-based calorimetry.

The STFI Apparatus

Shortly after the Sensenig apparatus was demonstrated, G. Svensson and B. Östman [46] used the same concepts to develop a method at the Svenska Träforskningsinstitutet (STFI,Swedish Forest Products Research Institute). Their method comprised a 150 × 150 mm vertically oriented specimen, heated by a radiant panel comprised of a bank of 12 infrared heat lamps (Figure 10). Unlike the high-temperature lamps used in the FMRC apparatus, the ones used by SFTI showed a peak spectral intensity at a more appropriate wavelength of 2.4 μm. This heater provided for maximum specimen irradiance of up to 50 kW/m². The specimen was mounted on a load cell. Ignition was from either a simple gas pilot, or from a line burner.

For some subsequent work, STFI constructed another experimental apparatus, which was similar to the Cone Calorimeter, but set up for larger specimens [47]. Neither of these STFI apparatuses are in regular use now. The work was
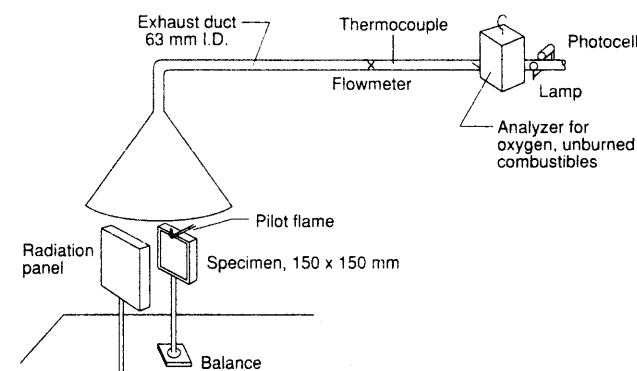

Figure 9. The Sensenig apparatus.

transfered to Tratek (Swedish Institute for Wood Technology Research) who turned to using the Cone Calorimeter.

The Cone Calorimeter

This apparatus was designed at NBS, primarily by V. Babrauskas, W.J. Parker, and D.E. Swanson, after experience had been gained with the desirable and undesirable features of a number of previous devices. The calorimeters routinely operated at NBS included the NBS-I, NBS-II, and the OSU apparatus. In pursuit of the best implementation of the oxygen consumption principle, a number of other purely-developmental calorimeters were also constructed. Different heating arrangements and various concepts for oxygen consumption gas trains were
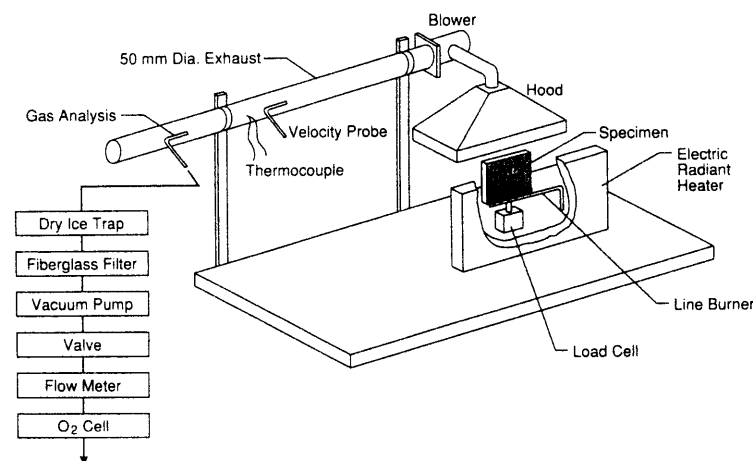

Figure 10. The STFI Apparatus.

explored in these units. The FMRC Small-scale Flammability Apparatus and the SRI Calorimeter were also studied in detail in this design process, although they were never installed or operated at the NBS laboratories. The instrument that resulted has been called the Cone Calorimeter, due to the truncated cone shape of the heater, and is described in detail in Chapter 4.

Additional experimental devices

A number of other studies have been reported in the development work leading to a viable method for rate of heat release measurement by oxygen consumption. A number of them have already been discussed above, in connection with exploring errors in the OSU apparatus and reducing those by use of oxygen consumption.

Other efforts included those of Alvares and co-workers at the Lawrence Livermore Laboratory [48]. Before obtaining their SRI calorimeter, they made a series of tests in a rate of heat release apparatus which was converted from the ASTM E 162 radiant panel flame test. Another effort was by Holmstedt and Wetterlund [49], who fitted the Swedish Box Test (which, in its standard form, does not have a proper calibration for rate of heat release and, therefore would not have been considered among the apparatuses for measuring heat release rate) with an oxygen consumption measuring rig.

Perhaps most fascinating was a method by Quintiere for using the flame length of a wall flame as a measure of heat release rate.[50] According to a simplified solution of the wall flame problem, the flame length x_f is proportional to the rate of heat release per unit specimen width, q', according to the relationship:

$$q' \propto x_f^{3/2}$$

Because of difficulties in reliably and reproducibly identifying the location of a flame tip, this method has only been used rarely to gather data, some of which are referred to in Chapter 17. It retains promise, however, for correlating data *a posteriori* [50], where flame lengths might have been recorded in conjunction with other measurements.

An interesting utilization of the oxygen consumption principle has been reported by workers at the NASA Langley Research Center [51], who applied it to gas calorimetry. They built a device for on-line measurement of the heat of combustion of natural gas samples, using an apparatus with a servo-loop system. The basic arrangement was a gas burner with an oxygen sensor in the exhaust

duct. Ahead of the sensor, a supplemental oxygen flow stream was introduced. The servo was set to maintain the oxygen sensor reading at a constant value, thus, the amount of oxygen supplied through the supplemental stream was a direct measure of the heat being released by the burning gas sample. This type of construction has not found an application in fire testing, however.

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